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Multi-Loop Integral Control-Based Heart Rate Regulation for Fast Tracking and Faulty-Tolerant Control Performance in Treadmill Exercises

Yi Zhang, Kairui Guo, Qin Yang, Pang Winnie,
Kai Cao, Qi Wang, Andrey Savkin, Branko Celler,
Hung Nguyen, Peng Xu, Limei Xu,
Dezhong Yao and Steven Su

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Abstract

In order to offer a reliable, fast, and offset-free tracking performance for the regulation of heart rate (HR) during treadmill exercise, a two-input single-output (2ISO) control system by simultaneously manipulating both treadmill speed and gradient is proposed. The decentralized integral controllability (DIC) analysis is extended to nonlinear and non-square processes especially for a 2ISO process, namely multi-loop integral controllability (MIC). The proposed multi-loop integral control-based HR regulation by manipulating treadmill speed and gradient is then validated through a comparative treadmill experiment that compares the system performance of the proposed 2ISO MIC control loop with that of single-input single-output (SISO) loops, speed/gradient-to-HR. The experimental validation presents that by simultaneously using two control inputs, the automated system can achieve the fastest HR tracking performance and stay close to the reference HR during steady state, while comparing with two SISO structures, and offer the fault-tolerant ability if the gains of the two multi-loop integral controllers are well tuned. It has a vital implication for the applications of exercise rehabilitation and fitness in relation to the automated control system.

Keywords: heart rate, treadmill exercise, decentralized integral controllability, multi-loop integral controllability, proportion-integral (PI)

1. Introduction

Obesity, which leads to diabetes and cardiovascular disease (CVD), is one of the major threats to human health. It is well recognized that regular exercise is the most efficient way to reduce

the possibility of both type 2 Diabetes and CVD [1]. The development of automated exercise assisted equipment can greatly enhance the efficiency of exercises and reduce the requirement of supervision. An easy-to-measure indication of exercise strength is heart rate (HR). One of the most efficient ways for the manipulation of exercise intensity for either the training of athletes or rehabilitation patients is to simulate the HR in order to follow a pre-designed HR profile. As a result, an automated control system can offer numerous benefits for different groups of users. For instance, it will provide assistance for patients with cardiac diseases who might be prescribed treadmill exercise rehabilitation. It also can be used for training the athletes and safely regulating the exercise intensity within a suitable profile in order to achieve the predefined HR ranges. It has been well documented that by determining one's maximum and minimum values of HR responses the exercise profile can be individually designed [2]. Specifically, rehabilitation patients will be guided to perform the exercise in terms of 50–60% of the maximum HR, 60–70% of the maximum HR zone then suitable for subjects who target weight control, and the range between 70 and 90% is preferred for the cardio-endurance exercise. In the study, a two-input single-output (2ISO) control system is proposed, which can specially further improve the efficiency of treadmill exercises for different subject groups as well as diversify more reliable and safe treadmill exercise protocols.

Recently, most studies [3–6] only consider using one manipulate variable (treadmill speed or gradient) to regulate HR responses. In [7, 8], for exercise testing and rehabilitation of subjects with impaired exercise tolerance, ramp type protocols were proposed by simultaneously manipulating both speed and gradient (without feedback), which could produce a low initial metabolic rate that then increases the work rate linearly to reach the subject's limit of tolerance in approximately 10 min. In [9], a multi-loop proportion-integral (PI) controller based HR tracking system has been presented, which independently tuned both treadmill speed and gradient in closed loop, and achieved good performance. However, in paper [9], it is assumed that the HR response to treadmill exercise is in linear range, and only linear modeling and control approaches have been presented. The experimental evidences of the advantages of using both speed and gradient to regulate HR are therefore only valid in a certain linear response range.

This study introduces the 2ISO HR process which employs two actuators, treadmill speed and gradient, to regulate the HR response. Such process control has the following merits. First of all, it can increase the non-saturation range. For example, practical systems always have physical limitations and therefore have limited non-saturation range. If simultaneously executing multiple actuators, the output range can be extended. On the other hand, it can increase the maximum gain of the actuator so that the fast tracking or regulation of manipulated variable can be achieved [9]. Also, redundancy of actuators can facilitate fault accommodation for the implementation of fault-tolerant control strategies. As the stability of the closed loop system can be practically achieved by adding suitable constraints in control inputs and their derivatives, the achievable performance (especially in steady state) is more important for most industrial control processes.

For the regulation of HR, multi-loop PI controllers were developed [9] in order to achieve zero steady-state tracking error. For multi-loop PI control of square process, Skogestad and Morari [10] introduced the concept of decentralized integral controllability (DIC). DIC analysis [11–13] determines the stability, integral control ability, and faulty-tolerant control of the multi-loop system. This study extends the DIC analysis for nonlinear and non-square processes especially

for a 2ISO process, namely multi-loop integral controllability (MIC). The proposed multi-loop integral control-based HR regulation by manipulating treadmill speed and gradient is then validated through a comparative treadmill experiment that compares the system performance of the proposed 2ISO MIC control loop with that of single-input single-output (SISO) loops, speed/gradient-to-HR. The real treadmill experiment is used to experimentally validate if MIC in the HR range is valid. Results show that, compared with two SISO loops, the 2ISO MIC control loop can achieve the fastest HR tracking performance, reach up to the reference HR during the steady state, as well as offer the fault-tolerant ability in the case of one of the gains of multi-loop integral controllers being out of service. It has a vital implication for the applications of exercise rehabilitation and fitness in relation to the automated control system.

2. Experiments

2.1. Experimental settings

In this study, the HR data during experiments were collected by a portable sensor, Alive Heart Monitor (HM131) manufactured by Alive Technologies. It consists of one HR sensor and one triaxial accelerometer. The HR data acquired from the internal HR sensor are used in the study. The sampling rate for HR data collections is 300 samples/s. A Bluetooth SPP connection is used to transmit the instantaneous HR data to the laptop-based control program that is designed and implemented based on LabVIEW (National Instrument). The treadmill Powerjog J series is set up for experiments, the speed and gradient of which is controlled and able to be accessed via the RS232 protocol. **Figure 1** shows the schematic diagram for the experimental equipment setup.

2.2. Subjects

Eight healthy non-smoking males were invited to join the experiments. They were free from any known cardiac or metabolic disorders, hypertension, and were not under any medication.

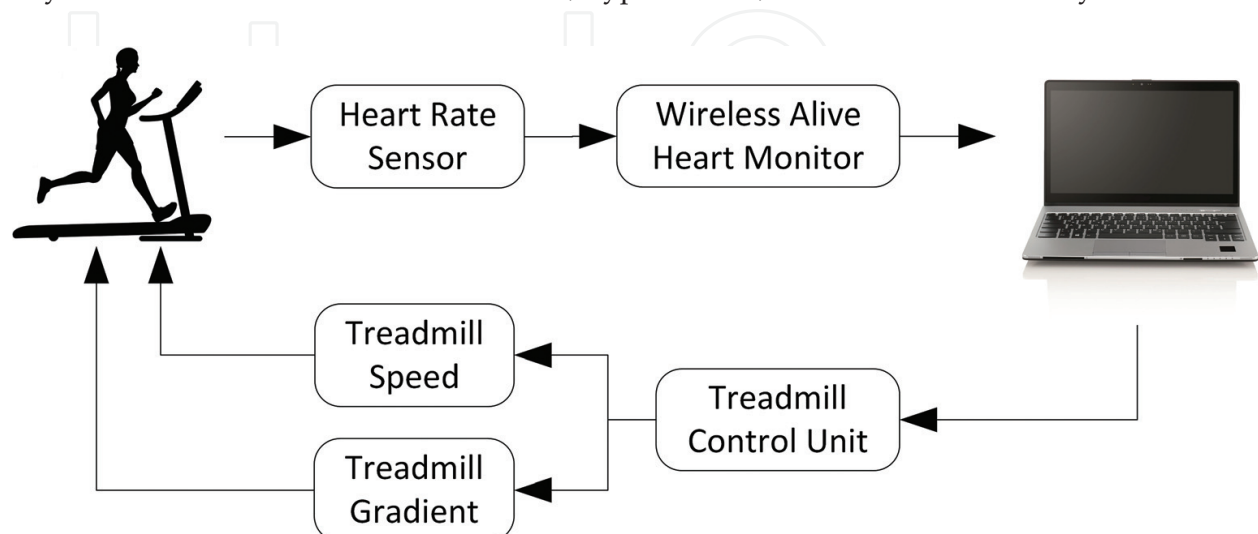


Figure 1. The schematic diagram for the experimental equipment setup.

The Human Research Ethics Committee by University of Technology Sydney (UTS HREC 2009000227) approved the study, and an informed consent was obtained from all participants before each experiment. The physical characteristics of the participants are presented in **Table 1**. The subjects were required to take a light meal prior to the experiment activity and not to participate in any intense exercises one day before the experiment [14–16]. The environmental temperature during the experiments was set at 25°C, and the humidity was at about 50% [17]. The HR monitor (HM131) was fitted to the middle of the chest of every subject by using electrode pads.

2.3. Experimental protocols

All subjects were asked to exercise on a motor-controlled treadmill, and they all selected 7 km/h as the speed for which both walking and running is possible. Then, subject was asked to walk for 5 min at 7 km/h for a certain gradient followed by a 7 min rest. This procedure was repeated for running as well as for different gradients. During experiments, HR response was recorded by the portable ECG monitor. The averaged steady-state HR of all subjects for both walking and running under different gradients is summarized in **Table 2**.

From **Table 2**, it can be seen that for a certain gradient, the HR for running is more than 15% higher than that for walking. During exercise, the subjects may switch between walking and running when the treadmill speed is around 7 km/h. As a result, it can be seen that, for example, when gradient is around 15°, the transition zone for HR is between 121 and 144 bpm. When the reference HR is located in the transition zone, the regulation of HR only by adjusting speed would be problematic even under small perturbations in the measurement. This is because the subject will frequently switch his/her motion actions between walking and

Subjects	Age (year)	Height (cm)	Weight (cm)
1	27	175	55
2	32	170	87
3	29	176	90
4	29	178	77
5	42	175	80
6	29	164	64
7	31	169	67
8	26	180	77
Mean	30.6	173.4	74.6
STD	4.7	5.0	11.1

Table 1. Physical characteristics.

Gradient (Degree)	HR (bpm) Walking at 7 km/h	HR (bpm) Running at 7 km/h
0	102	125
15	121	144
25	137	171

Table 2. HR response at steady state.

running in order to stabilize his/her desired HR level. As a result, simultaneous manipulating of speed and gradient would be firmly beneficial.

2.4. Pan-Tompkins HR detection

The Pan-Tompkins algorithm was applied to identify the P-peak of QRS complex during experiments, which is then used for calculations of HR values. This algorithm is inclusive of several filtering such as a band-pass filter, a differentiator, a squaring operation and a moving window integrator [9]. The band-pass filter is used to reduce noises in the raw ECG signals. After band-pass filtering, the high frequency components of ECG signals were extracted by using a five-point derivative function. The squaring operation was adopted to suppress P and T waves and further enhance the higher frequency QRS complexes. Finally, the moving window integrator provided a single peak output, P-peak, for each QRS complex. After implementing these steps and by implementing an adaptive threshold algorithm with false peak detection capabilities, the HR signals can be detected accurately [18].

3. Methodology

3.1. Multi-loop integral controllability analysis for HR responses to treadmill exercise

In [8], the multi-loop PI controller has been designed for the regulation of HR for treadmill exercise. Now, we consider the case when one of the actuators is in faulty condition. First, we introduce a definition of MIC, which is a direct extension of DIC for a non-square 2ISO process [19].

As shown in **Figure 1**, assume the HR response can be described by the following equations with an input vector $u \in R^2$ and an output vector $y \in R^1$:

$$P \begin{cases} \dot{x} = f(x, u) & x \in X \subset R^n, u \in U \subset R^2 \\ y = g(x, u) & y \in Y \subset R^1 \end{cases} \quad (1)$$

where the state $x(t)$ is determined by its initial value $x(0)$ and the input function $u(t)$. Considering the system (1) has equilibrium at origin, that is, $f(0, 0) = 0$ and $g(0, 0) = 0$, if the equilibrium x_e is not at origin, a translation is then needed by redefining the state x as $x - x_e$ [19, 20].

3.1.1. Definition 1

(Multi-loop integral controllability for nonlinear 2ISO processes) Consider the closed loop system depicted in **Figure 2**.

- i. For the nonlinear process P described by Eq. (1), if a multi-loop integral controller C exists, such that the unforced closed loop system ($r = 0$) is globally asymptotically stable (GAS) for the equilibrium $x = 0$ and such that the globally asymptotically stability is satisfied if each individual loop can be detuned independently by a factor k_i ($0 \leq k_i \leq 1$, $i = 1, 2$), then the nonlinear process P is said to be multi-loop integral controllable (MIC) for the equilibrium $x = 0$.

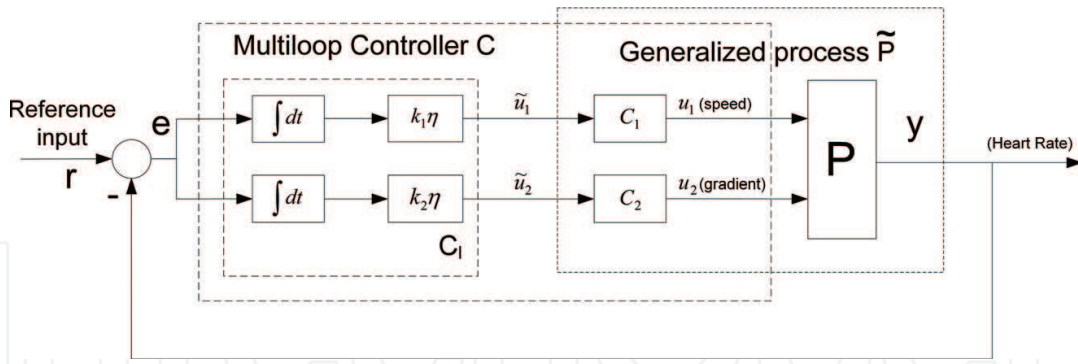


Figure 2. Multi-loop integral controllability for 2ISO system.

- ii. If the closed loop system is asymptotically stable (AS) near the region of the equilibrium $x = 0$, then the nonlinear process P is said to be locally multi-loop integral controllable around the equilibrium $x = 0$ [19, 20].

In **Figure 2**, we assume the state equation of the general process \tilde{P} (which includes original process P and the two scalar non-integral controllers c_1 and c_2) is modeled as follows (with the same assumptions for Eq. (1) of process P):

$$\tilde{P} : \begin{cases} \dot{x} &= f(x, \tilde{u}) \\ y &= g(x, \tilde{u}) \end{cases} \quad (2)$$

The state equation for the linear integral controller is expressed as:

$$C_l : \begin{cases} \dot{\xi} = \begin{bmatrix} \dot{\xi}_1 \\ \dot{\xi}_2 \end{bmatrix} = \eta \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} e = -\eta \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} y \\ \tilde{u} = \xi \end{cases} \quad (3)$$

The following theorem presented a sufficient condition for MIC:

3.1.2. Theorem 1

(Steady-state MIC conditions for nonlinear 2ISO processes).

Consider the closed loop system in **Figure 1**, and assume that the general process \tilde{P} and the linear part of the controller C_l are described by Eqs. (2) and (3), respectively. If the following assumptions are satisfied:

- i. The equation $0 = f(x, \tilde{u})$ obtained by setting $\dot{x} = 0$ in Eq. (2) implicitly defines a unique C^2 function $x = h(\tilde{u})$ for $\tilde{u} \in \tilde{U} \subset \mathbb{R}^2$.
- ii. For any fixed $\tilde{u} \in \tilde{U} \subset \mathbb{R}^2$, the equilibrium $x = h(\tilde{u})$ of the system $\dot{x} = f(x, \tilde{u})$ is globally asymptotically stable (GAS) and locally exponentially stable (LES).
- iii. If two C^2 functions can be found $\phi_1(\cdot)$ and $\phi_2(\cdot)$ such that that the steady-state input output function $g(h(\tilde{u}), \tilde{u})$ of the general process \tilde{P} satisfies the following requirements:

$$(\varphi_1(\tilde{u}_1) + \varphi_2(\tilde{u}_2)) \left(k_1 \frac{\partial \varphi_1(\tilde{u}_1)}{\partial \tilde{u}_1} + k_2 \frac{\partial \varphi_2(\tilde{u}_2)}{\partial \tilde{u}_2} \right) g(h(\tilde{u}), \tilde{u}) > 0 \quad (4)$$

(when $\varphi_1(\tilde{u}_1) + \varphi_2(\tilde{u}_2) \neq 0$ and $\tilde{u} \in \tilde{U} \subset R^2$) and $(\varphi_1(\tilde{u}_1) + \varphi_2(\tilde{u}_2)) \left(k_1 \frac{\partial \varphi_1(\tilde{u}_1)}{\partial \tilde{u}_1} + k_2 \frac{\partial \varphi_2(\tilde{u}_2)}{\partial \tilde{u}_2} \right) g(h(\tilde{u}), \tilde{u}) > \rho |\varphi_1(\tilde{u}_1) + \varphi_2(\tilde{u}_2)|^2$ (for some scalar $\rho > 0$) for in a neighborhood of $\varphi_1(\tilde{u}_1) + \varphi_2(\tilde{u}_2) = 0$.

Then there exists $\eta > 0$, such that the equilibrium is GAS. That is, if the two scalar controllers c_1 and c_2 can be found such that the generalized process \tilde{P} can satisfy Conditions (i), (ii) and (iii), then the nonlinear 2ISO process is MIC for the equilibrium.

Remark: If the generalized process \tilde{P} can be guaranteed to satisfy Conditions (i), (ii) and (iii), based on Theorem 1 it is said that the nonlinear 2ISO process can be MIC. Once the control system is assumed as nonlinear 2ISO MIC, the stability of system can be easily guaranteed by independently tuning the factor k_i . In practice, the factor k_i usually can be manually configured to be $0 \leq k_i \leq 1$, $i = 1, 2$.

The Proof of the above theorem (similar as that of Theorem 1 in [11]) is based on singular perturbation theory [18] and can be found in [19].

Based on Definition 1, we can easily check that a necessary MIC condition for a 2ISO process in each single loop is DIC respectively. For HR regulation system, the necessary condition for the speed-HR and gradient-HR subsystems is DIC respectively.

A sufficient DIC condition for SISO system is the passivity in steady state, that is, the sector condition for passivity. We can easily prove that this condition is also sufficient for 2ISO processes based on Theorem 1.

For the HR responses during walking or running exercises, it is not hard to see that the incremental increasing of speed or gradient respectively will lead to the incremental increasing in HR for the same exerciser, that is, each single loop is DIC in either walking zone or running zone. However, the HR variation during walking and running transition is not clear. The following parts simulated the transition of walking/running as well as performed several experiments to investigate the HR response during transition between walking and running [21].

We also explore the offset free tracking when one of the actuators is in faulty conditions. We consider the case when one of the motors (speed motor and gradient motor) is broken, whether HR tracking is still possible or not. We also investigate whether offset free tracking is achievable or not under faulty conditions [22, 23].

4. Results

4.1. MATLAB®/Simulink® simulation verification

In order to identify the coefficients of PI controllers and verify the proposed MIC conditions for 2ISO HR regulation, the SISO and 2ISO control loops are designed and implemented through MATLAB®/Simulink® simulations. The schematic diagram for simulations is illustrated in

Figure 3, where the constructed HR model is regulated by either treadmill speed/gradient (the SISO loops) or both of those actuators (the 2ISO loop).

A two-input single-output Hammerstein model is used for modeling of HR-based open-loop characteristics. The linear dynamic part of the model is noted as $G(s) = \frac{K}{Ts+1}$, where K and T are the steady state gain and the time constant, respectively [24, 25]. The static nonlinear part is modeled by a cubic polynomial function. The input-output relationship between treadmill speed and heart rate is shown in **Figure 4** when the gradient is zero.

Based on the previous experimental survey in [9], the multi-loop integral controllers for the single loops of speed-HR and gradient-HR are developed respectively. The experimental results confirm the static nonlinearity of HR responses to treadmill walking/running exercises which has been shown in **Figure 8**. As a result, the passivity sector condition can be found in the zones of 0–6.8 km/h (indicating the walking condition), and 7.2–7.8 km/h (indicating the running condition). This means when treadmill speed is within the walking zone, for instance, the subject merely needs to undergo a walking motion to follow the treadmill protocol. Moreover, if the treadmill speed reaches the running zone, the running motion has to be taken by all of subjects. However, it also could be observed from **Figure 4** that the passivity sector condition in the transition zone from 6.8 to 7.2 km/h is not valid. This means that if the reference HR variation is selected as 49.5374 (HR is 124.5374 bpm) which is located in the transition zone, the regulation of HR by only adjusting speed would be problematic even under small perturbations in the measurement. This is because the subject will frequently switch his/her motion actions between walking and running in order to stabilize his/her desired HR level.

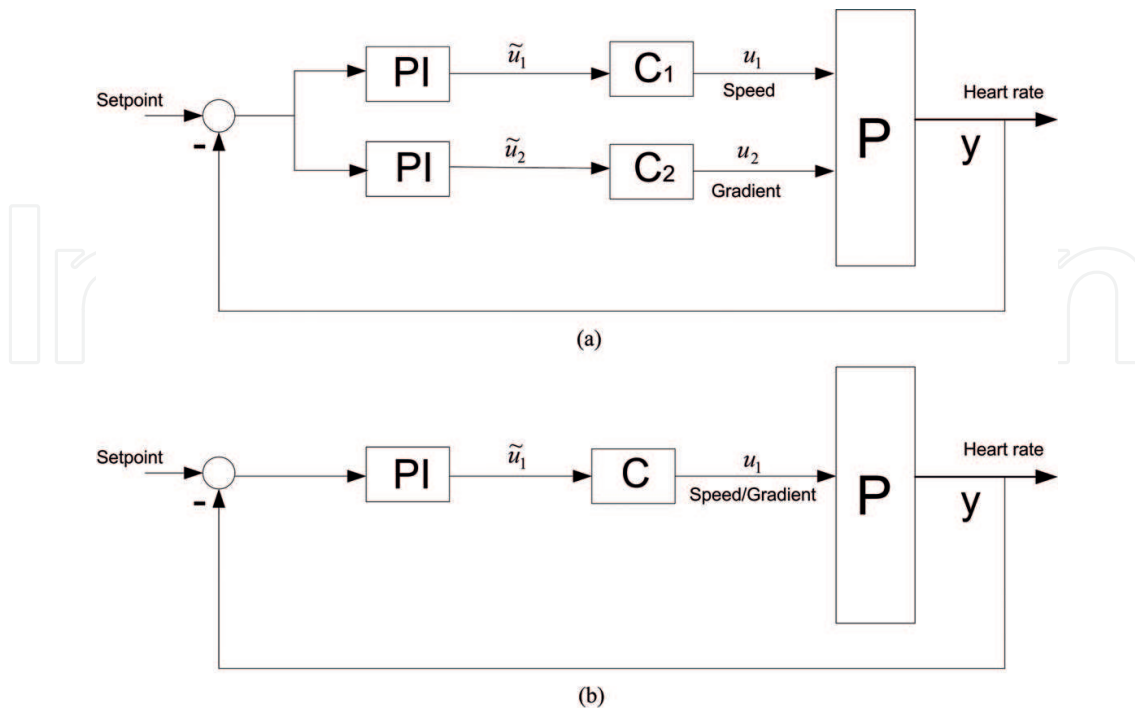


Figure 3. The schematic diagram of 2ISO PI control structure for MATLAB®/Simulink®-based HR tracking simulation. a. HR tracking of 2ISO control loop and b. SISO control loop of speed-HR or gradient-HR.

Figure 5 shows the simulation result for which only speed has been manipulated. This indicates another advantage for the using of two control inputs and fault tolerance. It can be proved based on Theorem 1 and also by simulation that if the open loop gain for healthy actuator is significantly

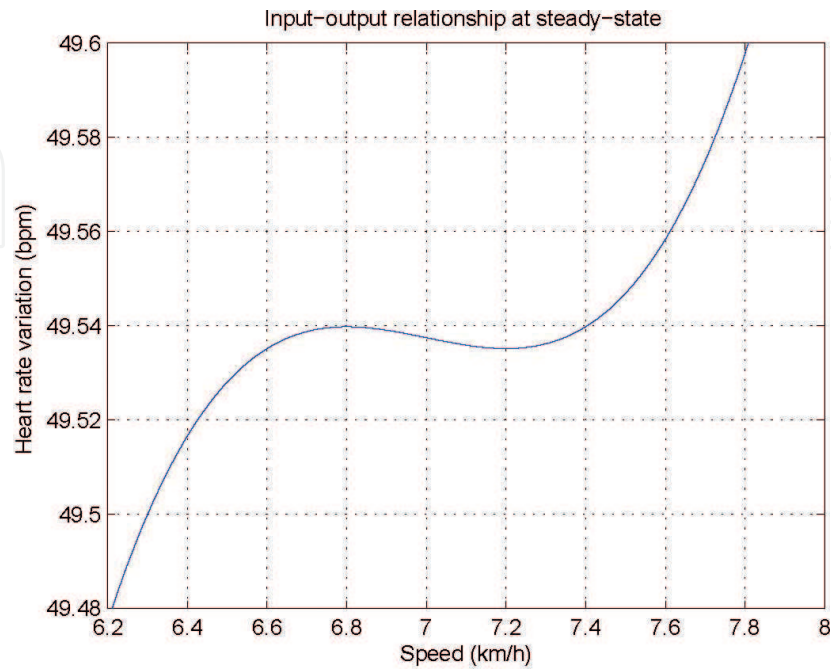


Figure 4. Steady-state HR response to speed (gradient is zero).

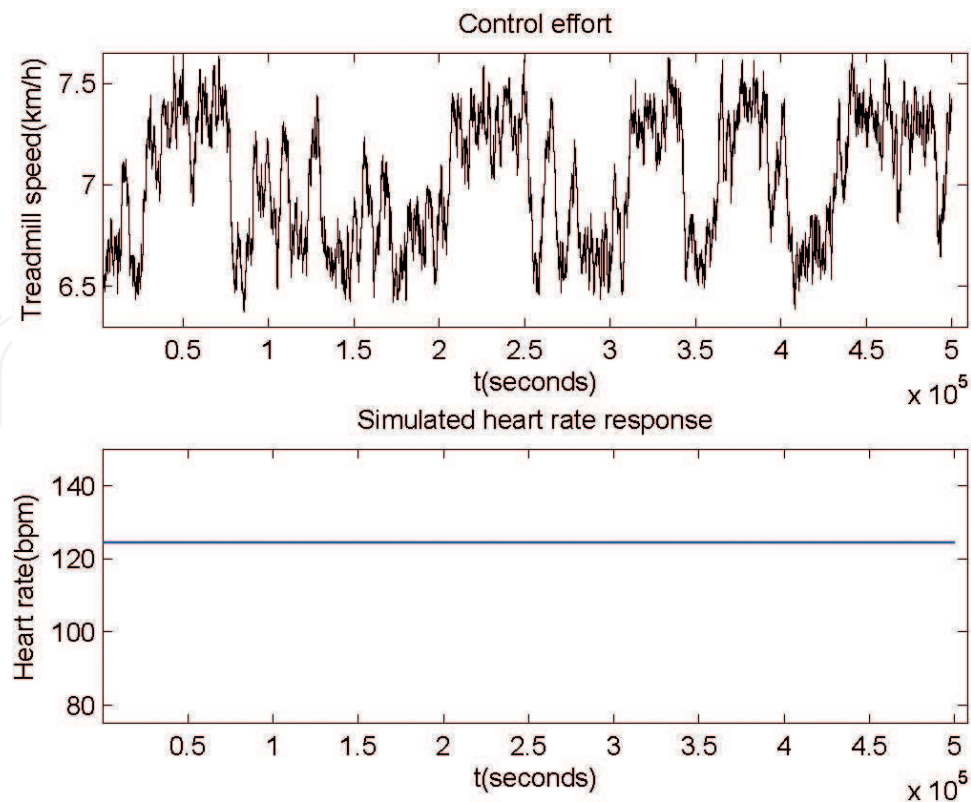


Figure 5. HR regulation results when only speed is manipulated.

bigger than that for faulty actuator, then the offset free tracking is still possible. Although the regulated HR is quite close to reference HR, treadmill speed swings between 6.5 and 7.5 km/h.

Due to the discomfort evoked by the speed swinging, we can simultaneously manipulate both treadmill speed and gradient and adjust the gradient regulation loop to avoid the swinging. Simulation results in **Figure 6** prove the effectiveness of the simultaneous manipulation strategy.

The simulation results from PI control loops of SISO (speed-HR and gradient-HR) and 2ISO indicate that those three structures can well achieve the HR tracking performance merely by tuning the PI parameters of multiple integral controllers with quite small values; the simultaneous manipulation strategy for the regulation of HR responses to treadmill exercises is effective if MIC conditions are satisfied; the 2ISO closed loop can provide the ability of fault tolerance which means that especially in the case of one of the actuators (either speed or gradient) being out of service, the offset free tracking is still achievable.

4.2. Experimental validation

In order to evaluate real-time HR tracking performance obtained from the proposed 2ISO control loop, the experimental verification is also used in this study, and a comparative study is made by comparing the tracking performance of the 2ISO loop with that of both SISO loops of speed-HR and gradient-HR.

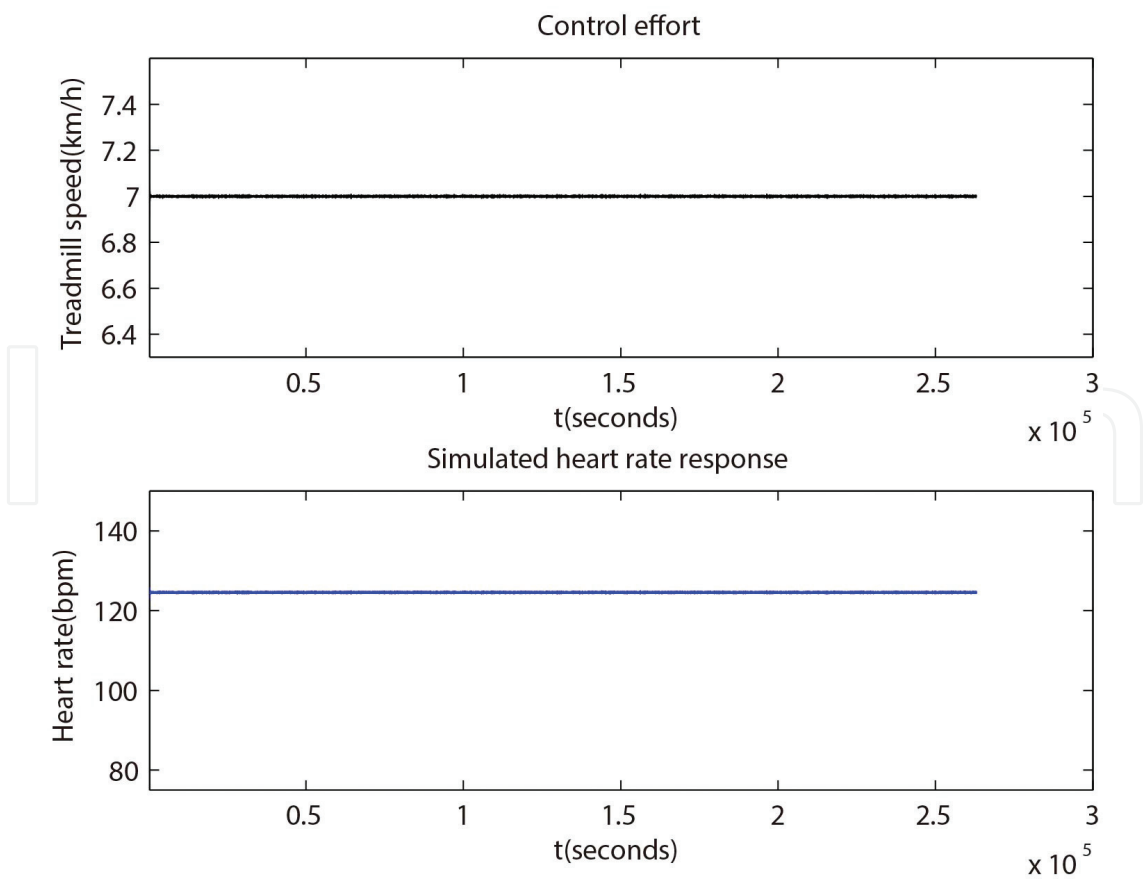


Figure 6. HR regulation results when both speed and gradient are manipulated.

In order to identify the comfort HR zones of each individual for treadmill experiments, moderate exercise intensity was adopted which offers safe treadmill intensity (speed ranged from 3 to 7 km/h, and gradient from 2 and 15%). This guarantees the HR operating zone for the subject to be located between 90 and 170 bpm. In addition, the HR level at 135 bpm was selected to be a reference input for the setpoint value of both SISO and 2ISO tests.

Considering the time-delay situation between control inputs (such as treadmill speed and gradient) and system output (instantaneous HR) during the practical experiment validation, a stack buffer with a 5-s timer was used to obtain the instantaneous HR values. The latest HR value was stored from the top of the stack buffer. The control input commands will be sent to the treadmill every 5 s based on the up-to-date stack buffer stores. For de-noising the raw instantaneous HR values measured by the Alive Technologies HR sensor, an improved exponential, weighted, moving, average filter together with a simple outlier detection algorithm was adopted for the estimation of the HR stored in the stack buffer [4].

In the first SISO open loop test, the speed of the treadmill is employed to be the system input, and HR is considered as the system output. Moreover, the gradient of treadmill is fixed at 2% and the input is set to be adjustable between 2 and 5 km/h. The PI parameters of speed-HR loop with a stable operation range 0.01–1.05 for k_p , 0.001–0.075 for k_i were determined. Based on the open loop experimental results, for the SISO controller with speed as the input, PI controllers, k_p and k_i , are set to 0.7 and 0.05, respectively, in order to achieve acceptable control characteristics. The HR response is shown in **Figure 7**, in which the HR model parameters K and T values were determined to be equal to 15.91 and 37.44, respectively. The results show the HR increasing quickly and a small reaction delay.

In addition, based on the gradient-HR test, a fixed speed of 4 km/h is maintained while the gradient is changed from 2 to 12%. The stable operation range (k_p :0.01–0.4665, k_i :0.001) for gradient-HR loop is observed from the experimental results. As a result, for the SISO controller with gradient as the input, k_p and k_i values are adjusted to 0.311 and 0.001 respectively. The coefficients for the speed-input controller slightly varied from the theoretical values, while in the case of the gradient-input controller, the theoretical values were acceptable. The response

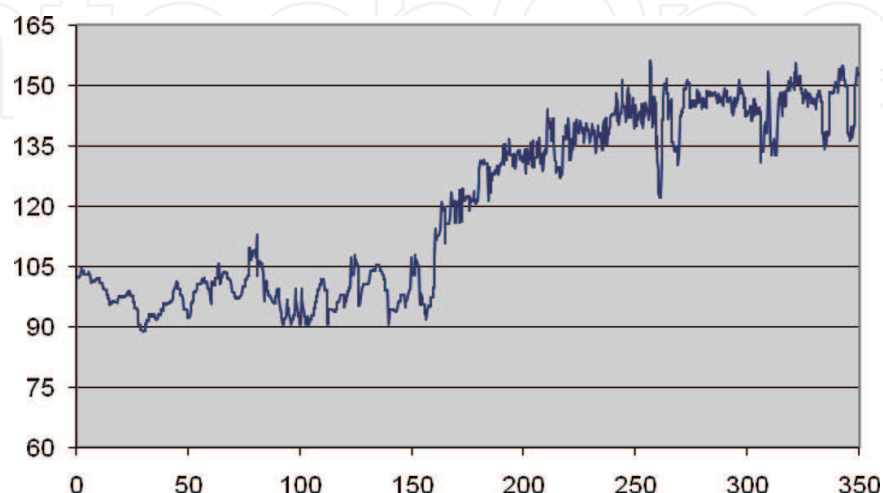


Figure 7. Experimental data for HR step responses to either treadmill speed or gradient (open-loop test with speed and HR).

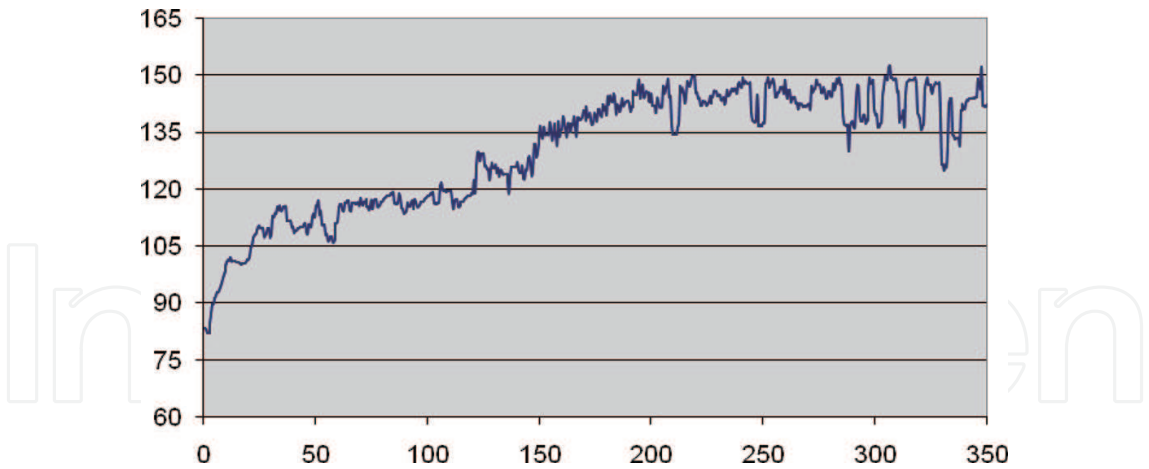


Figure 8. Experimental data for HR step responses to either treadmill speed or gradient (open-loop test with gradient and HR).

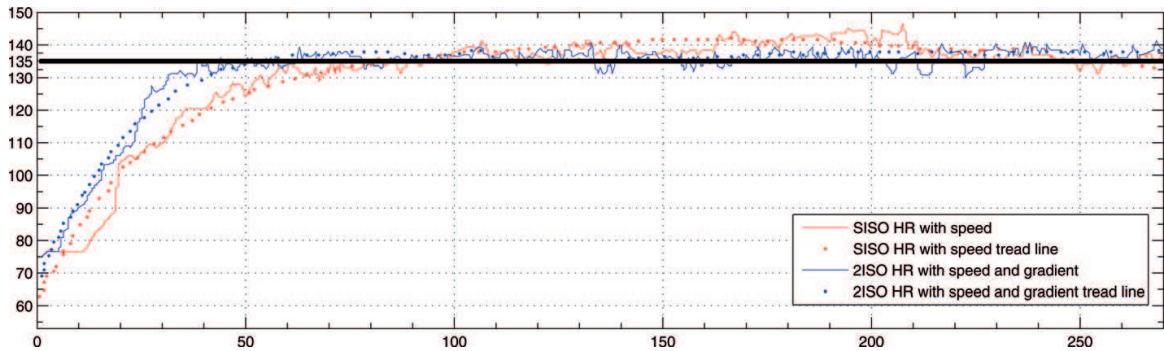


Figure 9. HR tracking performance comparison of SISO (speed) test with 2ISO.

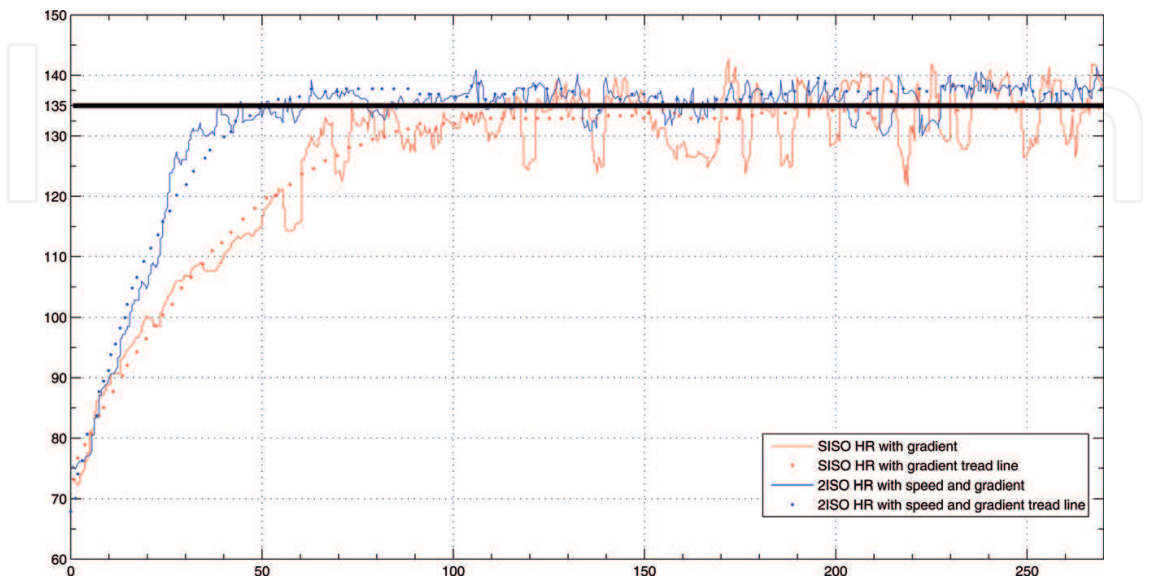


Figure 10. HR tracking performance comparison of SISO (gradient) test with 2ISO.

graph is shown in **Figure 8**, where K and T values obtained are 2 and 26, respectively. A reaction delay can be observed due to the mechanical time that the treadmill needs to reach the desired gradient.

Using experimental verification results with the determined PI coefficients, two closed loop SISO controllers and one 2ISO controller were implemented. **Figures 9** and **10** provide a clear view of both SISO control with speed-input and gradient-input compared with 2ISO. For the SISO speed-input controller, it demonstrates that the system outputs have a slight overshoot followed by a fast rise to track the setpoint. However, for the SISO gradient-input controller, it shows a more stable performance compared to that of the SISO speed-input controller. The comparative results shown in **Figure 10** demonstrate that 2ISO control loop can achieve the fastest HR tracking performance and stay close to the reference HR during steady state, while comparing with two SISO structures.

The main advantage of using 2ISO control in treadmill exercises is to improve the HR tracking performance. It can be concluded that the 2ISO controller outperforms both SISO controllers and can provide shorter rise time, best steady-state stability, as well as the lowest steady-state error. In addition, the 2ISO automatic treadmill exercise system also offers more comfortable and safer exercise conditions for users.

5. Conclusion

This study investigates the benefits of using two controller inputs, the speed and gradient, for the regulation of HR during treadmill exercises. The main goal of HR control in treadmill exercises is to ensure a reliable, fast, and offset-free tracking, as well as to offer the faulty tolerance ability in the case of one of actuators (either treadmill speed or gradient) being out of service. For this purpose, we extended the concept of nonlinear decentralized integral controllability (DIC) to nonlinear 2ISO processes and presented a sufficient condition which only needs checking the steady state input-output relationship of controlled processes. Based on the proposed condition, we investigate the new defined multi-loop integral controllability (MIC) for walking, running, and walking-running zones. The experimental validation presents that by simultaneously using two control inputs, the automated system can achieve the fastest HR-tracking performance and stay close to the reference HR during steady state, while comparing with two SISO structures and offer the fault-tolerant ability if the gains of the two multi-loop integral controllers are well tuned. It has a vital implication for the applications of exercise rehabilitation and fitness in relation to the automated control system.

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Nomenclature

AS	Asymptotically stable
BPM	Beat per minute
ECG	Electrocardiography
GAS	subject to be located between
HR	Heart rate
PI	Proportion-integral
DIC	Decentralized integral controllability
MIC	Multi-loop integral controllability
CVD	Cardiovascular disease
2ISO	Two-input single-output
SISO	Single-input single-output
STD	Standard deviation
UTS	University of Technology Sydney

Author details

Yi Zhang^{1,2,3}, Kairui Guo⁴, Qin Yang¹, Pang Winnie¹, Kai Cao⁴, Qi Wang⁵, Andrey Savkin⁶, Branko Celler⁶, Hung Nguyen⁴, Peng Xu^{2,3}, Limei Xu¹, Dezhong Yao^{2,3} and Steven Su^{4*}

*Address all correspondence to: steven.su@uts.edu.au

1 School of Aeronautics and Astronautics, University of Electronic Science and Technology of China, Chengdu, China

2 Key Laboratory for NeuroInformation of Ministry of Education, School of Life Science and Technology, University of Electronic Science and Technology of China, Chengdu, China

3 Center for Information in BioMedicine, University of Electronic Science and Technology of China, Chengdu, China

4 Centre for Health Technologies, Faculty of Engineering and Information Technology, University of Technology, Sydney, NSW, Australia

5 Hapatobiliary Surgery Department, General Hospital of Ningxia Medical University, Ningxia, China

6 School of Electrical Engineering and Telecommunications, University of New South Wales, Sydney, NSW, Australia

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